A High-Resolution Thermometer for the Range 0.75 - 1.0 K

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Abstract

We report on a new high-resolution thermometer (HRT) for use near the tricritical point in ^{3}He-^{4}He mixtures. It is based on an existing HRT design that uses a DC-SQUID to detect the magnetization of a paramagnetic sensing element. We present the first test results of an HRT using a gadolinium gallium garnet (GGG) crystal. Sensitivity over the temperature range 0.4 to 3.5 K for applied fields from 0.41 to 20 Gauss is presented.

Keywords: Thermometer, ^{3}He-^{4}He Mixtures, Tricritical Point, Gadolinium Gallium Garnet

1. Introduction

HRT's based on paramagnetic salts or palladium alloys have proven extremely useful in a wide range of helium physics experiments. However, these HRT's are designed to work at temperatures > 1 K, while the EXACT project (EXperiments Along Coexistence near Tricriticality) requires a thermometer with resolution of about 1 nK over the temperature range from 0.75 to 1.0 K to study the tricritical point of ^{3}He-^{4}He mixtures (T=0.87 K). We discuss and present initial results of an HRT using GGG. This material has important advantages over previously developed materials in that it is commercially available in pure single crystal form and has excellent environmental stability.

GGG has been studied extensively[1] for use as a magnetic refrigerant, therefore much is known about its magnetic and thermodynamic properties. Measurements of the magnetic susceptibility[2] lead to the conclusion that an HRT using GGG has the potential to achieve sub-nK resolution.

The resolution of an HRT is given by

$$\delta T = \frac{\delta\phi_{sq}}{f A_{eff} B_0 (\partial\mu/\partial T)} \tag{1}$$

where $\delta\phi_{sq}$ is the flux noise of the SQUID, f is a flux transfer factor, A_{eff} is the effective area of the pickup coil, B_o is the bias field, and μ is the magnetic susceptibility of the material. When Eq. 1 is used with the known properties of GGG, it suggests resolution of tens of pK, but intrinsic thermal fluctuations[3] in a GGG crystal sized for use in an HRT and mounted in the conventional way will limit it to a resolution in the nK range.

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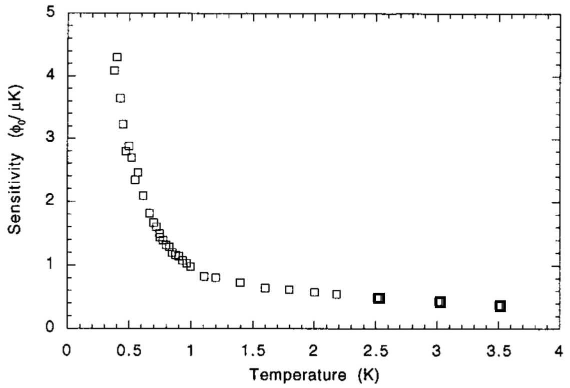

Fig. 1. Sensitivity over a wide temperature range for field B = 16 G.

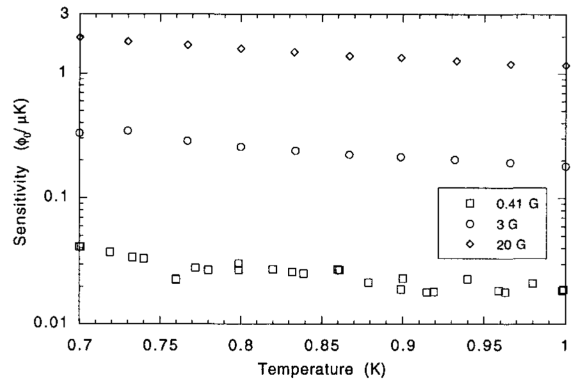

Fig. 2. Sensitivity over a narrow temperature range for several fields.

2. HRT Description and Results

The design of our HRT follows the previous one by Badaar[4]. A superconducting pickup coil couples the input coil of the DC SQUID to changes in magnetic field in the GGG caused by temperature changes. Permanent magnets mounted outside the flux shield provide the initial field trapped by the niobium flux tube as it cools through its superconducting transition. The number and spacing of the magnets is changed to provide different magnitudes of bias field. The entire test apparatus is enclosed in a dipper-style ^{3}He refrigerator.

The measured sensitivity for one value of applied field over a wide temperature range, from 0.4 to 3.5 K, is shown in Fig. 1. The upward curvature is consistent with measurements of susceptibility by Fisher[2]. Similar results for a narrower temperature range and additional fields are shown in Fig. 2. Given a typical SQUID resolution of $1 \times 10^{-5}\phi_0$, sub-nK temperature resolution may be achievable if the GGG is well thermally anchored.

The field B = 0.41 G was obtained without any permanent magnet in place, and is just the vertical component of the local value of the geomagnetic field. The sensitivity at this field was used to scale the fields seen in the other data sets. The sensitivity at 0.70 K was used to find the appropriate scale factor for the other fields. From this scaling, we infer that the values of the trapped fields are approximately 3, 16, and 20 G. These values are consistent with the number and spacing of permanent magnets used in each case.

The measured sensitivity is sufficient to allow 1 nK resolution over the temperature range 0.75 to 1.00 K using a DC SQUID and bias fields of only a few Gauss. The sensitivity at higher temperatures, including T_λ (2.1768 K) and the critical point of ^{3}He (3.314 K), may allow GGG to function as an HRT material for other investigations at these higher temperatures using higher bias fields.

Future work will measure sensitivity at higher fields, drift against a fixed point device, and thermal time constants, as well as improve the thermal design of the HRT. This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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